BILINGUAL PUBLISHING GROUP

Journal of Environmental & Earth Sciences

https://journals.bilpubgroup.com/index.php/jees

ARTICLE

CO_2 Emissions among Industrialized Countries amidst Climate Change: South Africa versus Other Selected BRICS Countries and the USA

Joseph Sello Kau [1*], ***Solly Molepo*** [2,3], ***Mamakie Lungwana*** [1], ***Ikechi Agbugba*** [4,5,6], ***Whitney Matli*** [1], ***Lesiba Pertunia Mailula*** [1]

[1] *Economic Analysis Unit, Agricultural Research Council, Pretoria 0028, South Africa*

[2] *Markets and Economic Research Centre, National Agricultural Marketing Council, Pretoria 0028, South Africa*

[3] *Faculty of Natural and Agricultural Sciences, North West University, Potchefstroom 2745, South Africa*

[4] *Faculty of Agriculture, Rivers State University, Port Harcourt 500106, Nigeria*

[5] *Business Management, York St John University, York YO31 7EX, UK*

[6] *Agribusiness Management, Rome Business School, Nigerian Campus, Lagos 100271, Nigeria*

ABSTRACT

Despite countries having signed agreements and developed policy to reduce CO_2 emissions, there is disproportionate compliance with the agreements, with developed countries continuing to be the largest emitters. The objective of this study was to compare the impact of South Africa's population growth, economic growth, and fertilizer consumption on CO_2 emissions, with those of the US, China, and other BRICS countries. The study used panel data sourced from the World Bank's World Development Indicators ranging from 1960 to 2023. Results of the fixed effects panel regression show that the coefficient of change for China's population size ($\beta = 9.156$, $p < 0.01$) is the highest among the six countries. It is followed by the USA ($\beta = 9.156$, $p < 0.05$) and South Africa ($\beta = 1.474$, $p < 0.01$). The effects of GDP for China ($\beta = 1.128$, $p < 0.01$) on CO_2 emissions are the largest, followed by South Africa ($\beta = 1.098$, $p < 0.01$) and the USA in third place ($\beta = 0.614$, $p < 0.05$). These results show that South Africa is highly reliant on coal-based energy resources. As a policy recommendation, South Africa needs to diversify its energy mix and invest more in renewable energy resources.

Keywords: CO_2 Emissions; Climate Change; GDP; Fertilizer Consumption; South Africa; US and China

*CORRESPONDING AUTHOR:

Joseph Sello Kau, Economic Analysis Unit, Agricultural Research Council, Pretoria 0028, South Africa; Email: kauj@arc.agric.za

ARTICLE INFO

Received: 7 October 2024 | Revised: 24 October 2024 | Accepted: 28 November 2024 | Published Online: 7 May 2025

DOI: https://doi.org/10.30564/jees.v7i5.7438

CITATION

Kau, J.S., Molepo, S., Lungwana, M., et al., 2025. CO_2 Emissions among Industrialized Countries amidst Climate Change: South Africa versus Other Selected BRICS Countries and the USA. Journal of Environmental & Earth Sciences. 7(5): 244–256. DOI: https://doi.org/10.30564/jees.v7i5.7438

1. Introduction

The world at large, greenhouse gas emissions especially CO_2, are responsible for a number of negative socio-economic outcomes, which manifest in the form of climate change and global warming. In the area of the environment, rainfall patterns have changed and are no longer predictable; there are increasing levels of temperature, and the atmosphere is warming up [1]. On the social front, humans are contracting all manner of diseases, especially chronic diseases emanating from poor diets, as households are no longer able to produce their own food due to declining quality of natural resources [2]. The negative economic effects manifest in the form of high unemployment rates due to job losses among industries depending on the environment, and this includes the agricultural sector [3]. The main contributing factor to global warming and climate change is CO_2 emissions. The impact of human carbon emissions on climate has generated widespread global concern [4].

In 2023, Asia had the highest percentage of weather-related disasters (36.9%), followed by the Americas (23.5%), Africa (22.4%), Europe (13.6%), and Oceania (3.6%). The Paris Agreement is a legally binding international convention addressing climate change. It was adopted by 196 parties at the UN Climate Change Conference (COP21) in Paris, France, on December 12, 2015, and went into effect on November 4, 2016. Its goal is to keep the increase in the global average temperature to well below 2 °C above pre-industrial levels and work to limit the temperature increase to 1.5 °C above pre-industrial levels [5]). The Paris Agreement has never succeeded in compelling countries, especially the most industrialized ones, from polluting the world.

The effects of greenhouse gas emissions extend beyond atmospheric warming, influencing urban thermal environments and ecosystem functionality. For instance, machine learning approaches have been employed to predict thermal responses to urban development in regions such as Nanjing, China [6]. Additionally, studies on global land surface temperature shifts reveal how these temperature dynamics influence primary productivity and carbon cycles, underscoring the need to understand climate interactions in regions with diverse landscapes and land use practices [7]. By incorporating broader environmental interactions, this study emphasizes the significance of adaptive strategies in land use and temperature regulation, highlighting the critical link between CO_2 emissions and global ecological impacts [8]. Greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), are central drivers of climate change, increasing the greenhouse effect and leading to higher global temperatures. The warming disrupts natural climate patterns, intensifying the frequency and severity of extreme weather events, such as unpredictable rainfall, prolonged droughts, and heatwaves [9]. These changes severely impact agricultural productivity, water availability, and human health, stressing ecosystems and communities worldwide.

The thermal environment, which refers to the temperature-related characteristics of a given area, is particularly sensitive to climate change and urbanization. Urban development, for example, increases surface temperatures through the urban heat island effect, where built-up areas become significantly warmer than surrounding rural regions. Studies using machine learning in regions such as Nanjing, China, reveal how urbanization intensifies these thermal impacts by replacing natural landscapes with heat-retaining materials like concrete and asphalt, further exacerbating temperature rises. The effect, coupled with overall global warming, creates localized heat stress that can lead to energy-intensive cooling demands, heightened air pollution, and increased health risks [10].

Land use changes, including deforestation, agriculture, and urbanization, are both a cause and effect of climate change [11]. The conversion of forests to agricultural land releases stored carbon into the atmosphere, increasing CO_2 levels. Land-use practices also influence carbon sequestration and affect ecosystem stability and biodiversity. Research on land transfer and carbon emissions in China highlights how shifts in land use contribute to rising carbon emissions, suggesting that carefully managed land policies could play a critical role in climate mitigation. Furthermore, changes in land surface temperature (LST) directly impact ecological productivity, as shown by studies analysing Gross Primary Production (GPP). Seasonal variations in LST can alter photosynthesis rates, affecting primary productivity and potentially disrupting food chains [12, 13].

Existing research suggests that developed countries such as China and India (part of BRICS) have high carbon emission abatement costs compared with large developing countries [14]. It is reported that in most developing countries, reductions in carbon emissions were caused by reductions in poverty and inherent natural conditions. Moreover, the extent of influence of a given factor on CO_2 emissions differed among countries [4]. Improving the level of green technology innovation is one way to improve carbon emission efficiency [15].

During the 2015, Paris convention on climate change, a few countries, including the BRICS and the US, pledged to reach net zero emissions by 2050 [16]. The net zero emissions mean lowering CO_2 emissions in line with the Paris global goal of keeping temperature increases to preindustrial levels of 1.5 degrees Celsius [17]. These countries are also signatories to the Kyoto Protocol [5–18]. Although there are policies across the world to control CO_2 emissions, there is disproportionate compliance with these policies, with several countries acting to violate them. As matters stand now, a few countries that signed the Paris Agreement are the ones emitting high levels of CO_2.

According to the United Nations 2023 [19] report, as of 2022, the US and the Russian Federation emitted high levels of CO_2, which was said to be more than double the world's average of 6.5 tons of CO_2 equivalent. At the same time, India emitted under half of the world's average. Brazil emitted slightly below the average of the G20, which at the time sat at a figure of 7.9 tons CO_2 equivalent. In 2021, China contributed about 18% to world climate change, and together the top seven global emitters, namely Brazil, China, India, Indonesia, the European Union, the Russian Federation, and the United States of America, accounted for 65% of global emissions [19]. South Africa, on the other hand, is an economic powerhouse in the African continent and highly industrialized. Based on the current policy framework, South Africa is projected to emit 6 tons CO_2 equivalent by 2030 [19].

South Africa is the leading greenhouse gas emitter in Africa, and this situation emanates from the fact that nearly 90% of the country's energy and electricity is derived from coal. As of 2022, South Africa was classified as one of the world's top 15 greenhouse gas (GHG) emitters [20]. Just recently, as of 2021, at the COP 26 meeting in Glasgow, a number of developing countries, comprising the US, Britain, France, Germany, and the EU, pledged funding to the tune of $8.5 billion to assist the country in moving away from its coal-based energy resources . Due to the devastating effects of climate change, there exists a large body of literature on CO_2 emissions. Running a search on Google Scholar and using the keyword "CO_2 emissions", the search returned 3,320,000 hits. Filtering the search further and using the keyword "South Africa CO_2 emissions" the search returned 405,000 publications. Most of the publications, however focused on looking at the factors contributing to CO_2 emissions. This suggests that there exists more room to study other facets of CO_2 emissions.

The objective of the study is to compare the impact of South Africa's population growth, economic growth, and fertilizer consumption towards CO_2 emissions with those of the US, China, and other BRICS countries. The aim is to benchmark South Africa against industrialised countries and its BRICS partners. The novelty of the study must be seen in the context of how variables derived from different sectors, e.g., those from the agricultural sector (fertilizer consumption and agricultural land) and those from the industrial economy (e.g., GDP growth and population growth), are balanced in the study. The study is important seeing that South Africa, being a developing country, still requires exploiting coal resources to grow its economy and create jobs, while on the other hand having to preserve the environment. Based on available literature, there is no study that has analysed South Africa in this context, with the closest studies being those of Sarkodie and Strezov and Rauf et al. [21, 22]. Sarkodie and Strezov [22] looked at the effects of foreign direct investments towards greenhouse gas emissions between South Africa, China, India, Iran, and Indonesia, whereas Rauf et al. [21] looked at the effect of foreign direct investments, technology, and economic growth among BRICS countries. Our study adds to the body of knowledge by establishing the underlying structural factors for South Africa's energy mix in relation to the US, China, and other BRICS countries.

2. Theoretical Framework

When it comes to deliberations regarding the issue of the relationship between CO_2 emissions and economic growth, the earlier work of Simon Kuznets, regarding the role of industrialization in enhancing income distribution between the rich and the poor is used as a framework for studying long-term effects of CO_2 emissions. Kuznet [23] hypothesised that in the earlier phase of industrialization (this being a major contributor to CO_2 emissions), there will be increasing inequality and that over time this will reach a peak, normalize and later decline. This has now come to be known as the Environmental Kuznets Curve (EKC) theory, simply demonstrated through an inverted U-shaped curve (see **Figure 1**). Specifically for CO_2 emissions, it is argued that for the world to reach a stage of a cleaner environment, there needs to be advancement in economic [24].

The BRICS countries, representing both developing and newly industrialized economies, exhibit different CO_2 emissions trajectories depending on their energy mixes, industrial bases, and regulatory environments. While developed countries may follow a downward EKC slope as economic growth brings environmental regulation and technological advancements, nations like South Africa and India may face challenges in achieving this due to economic and infrastructural constraints [21–25].

In BRICS nations, energy reliance varies: China and India heavily depend on coal, whereas Brazil has made significant strides with renewable energy, leading to distinct differences in emissions trajectories. South Africa's dependence on coal situates it uniquely within the EKC framework, where economic growth without energy diversification risks accelerating environmental degradation [15].

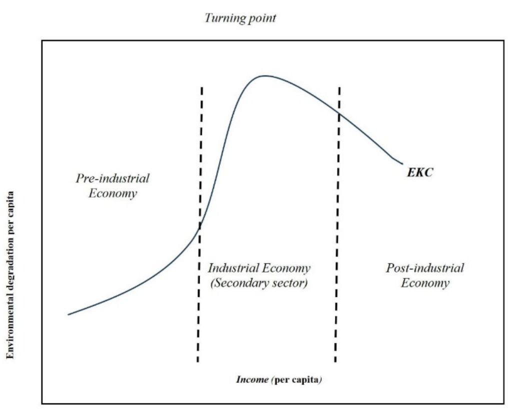

Figure 1. Environmental Kuznets Curve.

Beckerman [26], gave an interesting context, where he indicated that in terms of the EKC-theory, although there is degradation of the environment in the early stage of economic development, the only way for countries to achieve clean environments is by way of countries getting rich. Economic growth provides incentives for nations to adopt technologies that bring about efficient use of energy resources [21], it brings diversification in the energy mix [27], and there are incentives for governments to implement laws that are focused on the preservation of the environment [28]. These arguments are peddled on the basis of an assumption that the world is free from corruption and that governments are underpinned by good governance [28], also ignoring the transmission of the effects of pollution across different regions in the world. The assumption of good governance has proven futile over time as polluters of the environment bribe corrupt politicians to pursue investments into CO_2 emitting industries [29].

The EKC theory has over the years been treated with skepticism. The report of the Club of Rome titled "The Limits to Growth" tabled in 1972 cautioned that economic growth will result in the depletion of energy resources unless governments shift to cleaner energy resources [30]. Incidentally, in 1973 the world was plunged into an oil crisis, thereby making a case for policymakers to rethink strategies for economic development [30]. In this context, other events that followed, namely the UN conference on the Environment in Stockholm, the Brundtland commission of 1987, and the 1992 Brazil Earth Summit are noteworthy [31]. More importantly, the report from the Brundtland commission, which has directed that development must be evaluated in the context of the three dimensions of life, encompassing environment, social, and economic, is now a generally accepted framework. This is because it also touches on issues of human health, this being another critical consideration when it comes to damages associated with CO_2 emissions.

For this paper, another theory on CO_2 emissions is the decoupling theory, initially proposed by von Weizsacker, cited in Wang, Jiang and Zhang [32]. Decoupling refers to the reduction of resource use and environmental impact while maintaining economic growth, achieved through technological advancements, changes in industrial structure and shifts in economic growth patterns. Decoupling theory posits that countries can reduce CO_2 emissions through two mechanisms. The first relates to the attainment of efficiency within the existing energy systems and products and the second relates to the adoption of technology (e.g., cleaner energy resources) that would lead to reductions of Greenhouse Gas Emissions [32]. Still on the issue of the EKC-theory and given the recent incidences of climate change and global warming, economic development has, to a large extent, only served to destroy the environment. A few studies on CO_2 emissions have been published, highlighting important contributing factors. Among many of the important ones include GDP and population growth, the negative effects of energy-intensive industries such as Transport, Mining, Manufacturing and Agriculture. In the study by Zarco-soto, Zarco-Periñán, and Sánchez-Durán [33], involving 145 Spanish cities with more than 50,000 people, it was found that cities with large populations emitted high levels of CO_2.

For a study that analyzed the relationship between GDP growth and CO_2 emissions among five Western African countries, for the period 2007–2014, it was established empirically, that GDP growth caused CO_2 emissions [34]. Doğan [35] found that in China, the Agricultural Sector was one of the critical sectors that increased the country's long-term CO_2 emissions. Waheed et al. [25] brought a different perspective regarding the role of Agriculture when it comes to CO_2 emissions. For the study he conducted in Pakistan, where he used secondary panel data spanning a period from 1990 to 2014, the researchers demonstrated that Agriculture through the production of biofuels and the planting of trees, i.e. forestation, had a positive impact towards the reduction of Greenhouse gases. Jebli and Youssef [36], for the study involving five North African countries, using panel data spanning the period 1980–2011, empirically provide that an increase in agriculture value added reduced CO_2 emissions. Both the EKC theory and Decoupling theory provides the basis for the analysis in this paper. It is hypothesized that South Africa even when it has a relatively small economy, due to its high reliance on coal-related energy, the effects of population growth and economic growth in relative terms, will have significant negative impacts, as those of developed countries.

Hypothesis 1 (H_1). *Economic growth, fertilizer and population growth in South Africa have significant negative impacts on CO_2 emissions comparable to those of the US and China.*

3. Materials and Methods

3.1. Dataset and Analytical Techniques

The criteria applied for the selection of countries is informed by the levels of CO_2 emissions in the respective countries. In this regard United States of America (US), China, India, Brazil, and Russia are recorded as high emitters. Variable selection was informed by literature review. The study used annual data sourced from the World Bank, world development indicators ranging from 1960 to 2023. The data collected include the following variables: carbon CO_2 emissions measured in kilograms per constant 2015 USA dollar of GDP ($lnECO2EPC_t$); death rate per 1,000 people ($DTRT_t$); in the context of this paper, the death rate serves as a proxy for the industries administering deaths. This includes industries such as health, mortuaries, medicine and pharmaceuticals, and transport, to mention a few. Other variables include fertilizer consumption in kilograms per hectare of arable land ($lnFRTCP_t$), agricultural land use measured in percentage of total land size ($AGRL_t$); fossil fuel consumption in percentage of total ($FFEC_t$); gross domestic product per capita measured in constant (GDPPC) 2015 USA dollar; total population measured in number ($lnTPOP_t$). The selected variables were included in the model to assess their relationship with the dependent variable. The reason for transforming variables into logarithms is due to the fact that original continuous data do not follow the bell curve. Therefore, log transformation makes it normal so that the statistical analysis results from this data become more valid. Furthermore, the log transformation reduces or removes the skewness of our original data.

3.2. Model Specification

The variables were transformed to logarithms to stabilise the variance. The analytical technique applied is panel analysis using fixed effect (FE) and random effect (RE). The choice of the model is justified by the type of study under consideration, which is panel in nature, and these techniques account for the effect of the dependent variable that is common or varies in all study areas. The departure point is to perform the Hausman test to determine which model is appropriate between fixed effect and random effect. The null hypothesis to be tested is that the preferred model is random effects, while the alternative hypothesis supports the adoption of the fixed effects. Therefore, it assesses whether the errors are correlated with their independent variables, while the null hypothesis opposes it. The fixed effects play a vital role in statistical inference; it accounts for certain variables that remain fixed across the entire observations.

These effects offer an opportunity to capture the individual features of parameters under study and control the impact on the results of interest. However, the random effects account for variability between different parameters within a bigger group. Therefore, the mathematical equation of fixed effects is expressed as follows:

$$y_{it} = \beta_0 + \Sigma_t^n(\beta_{yxt}x_{it}) + \epsilon_{it} \tag{1}$$

Where y_{it} is the CO_2 rate of emission and ϵ_i is the random error term with a mean of 0 and variance σ_ϵ^2, while the β_1 represents the regressors included in the CO_2 rate of emission model. Therefore, the specific model for the Panel Dynamic CO_2 rate of emission model is illustrated as follows:

$$\begin{aligned} \tfrac{1}{6}\Sigma_{t=1}^{6} Y_{it} = \tfrac{1}{6}|\Sigma_{t=1}^{10}(\beta_1 DTRT_{1t} + \beta_2 FRTCP_{2t} \\ +\beta_3 AGRL_{3t} + \beta_4 FFEC_{4t} + \beta_5 GDPPC_{5t} \\ +\beta_6 TPOP_{6t} + \epsilon_t \end{aligned} \tag{2}$$

The description of the model is similar to the fixed effects model, but the difference between the two models is that random effects do not have an intercept. The mathematical equation for the Hausman test is expressed as follows:

$$HM_t = F(\beta_{FE} - \beta_{RE})^2 \tag{3}$$

Where, the Hausman is expressed as the squared variance between regression coefficients obtained from the fixed effects model (FEM) and random effects model (REM).

Hausman Test Procedure

The first step of analysing the results was to estimate the fixed and random effects model; thereafter, the Hausman test was performed to check which model is more appropriate. The CO_2 emissions measured in metric tons per capita were used as the dependent variable for both models.

The following variables as discussed in Section 3.1, were used as the independent variables: InDTRT$_t$; InFRTCP$_t$; InAGRL$_t$: InFFEC$_t$; InGDPPC$_t$ and InTROP. GDP per capita, population size, fertilizer consumption, agricultural land use, fossil fuel consumption, and death rate. Each of these relates to CO_2 emissions as follows: GDP per capita and population size drive energy demand and industrial activities, leading to increased CO_2 emissions [21, 37]. Fertilizer consumption and agricultural land use contribute through energy-intensive processes and land-use changes that release carbon [36–38]. Fossil fuel consumption directly emits CO_2 during the production of energy, while the death rate serves as a proxy for emissions from healthcare-related sectors [3–32].

The number of observations included under this panel is 147 and 6 countries. The sixty-three years of data starting from 1960 to 2023 have been applied in this study. However, due to the outcomes of the Hausman test, the random effects results are not considered as they were not found to be an appropriate model.

4. Results and Discussion

This section presents the current study's results. It starts off with summary statistics of the major variables used in the descriptive and later delves into the results of the empirical evidence.

4.1. Descriptive Results

Table 1 presents the results of descriptive analysis focusing on key important variables, which are fertilizer and CO_2 emissions. Looking at **Table 1**, the mean values for fertilizer consumption are high in Brazil, China, India, and the US. For Brazil the mean values are not statistically significant. Mean values for CO emissions are high for Russia, India, and China, with South Africa coming in at position number 4. For Russia, the mean value is not statistically significant.

Table 1. Descriptive analyses for key variables, fertilizer and CO_2 emissions.

Summary	BRAZIL_FERT	BRAZIL_CO2	CHINA_CO2	CHINA_FERT	INDIA_CO2	INDIA_FERT	RUSSIA_CO2	RUSSIA_FERT	SA_CO2	SA_FERT	US_CO2	US_FERT
Mean	275.58	0.24	1.24	270.07	1.28	141.14	4.08	35.77	1.32	63.43	0.36	118.52
Median	186.67	0.241	1.19	298.49	1.194	132.01	2.06	15.53	1.34	59.59	0.36	119.08
Maximum	803.66	0.27	2.12	458.52	1.79	236.43	12.37	92.14	1.50	104.64	0.50	135.56
Minimum	67.76	0.22	0.66	82.51	1.028	73.52	1.18	10.02	1.16	47.33	0.22	99.97
Std. Dev.	221.9138	0.02	0.38	123.53	0.25	51.98	4.12	33.74	0.08	13.21	0.09	10.74
Skewness	1.308786	0.11	0.66	–0.30	0.98	0.34	1.16	0.98	–0.18	1.86	–0.08	–0.17
Kurtosis	3.368996	1.95	2.86	1.90	2.38	1.77	2.44	2.12	2.64	5.54	1.71	1.79
Jarque-Bera	9.317125	1.55	2.34	2.11	5.58	2.64	7.64	6.12	0.35	27.09	2.25	2.12
Probability	0.009480	0.46	0.31	0.35	0.06	0.27	0.02	0.05	0.84	0.00	0.32	0.35
Sum	8818.643	7.78	39.75	8642.35	41.03	4516.53	130.86	1144.57	42.43	2029.86	11.64	3792.54
Sum Sq. Dev.	1526.618	0.01	4.41	473060.5	1.91	83749.72	525.21	35288.25	0.20	5411.02	0.24	3572.46
Observations	32	32	32	32	32	32	32	32	32	32	32	32

4.2. Inferential Results

For the Hausman test analysis, **Table 2** shows the results of fixed and random effects panel regression for CO_2 emissions among countries within the BRICS block, in comparison with the United States of America (USA). All included variables are statistically significant at various 1% probability levels under fixed effects, with only fertilizer consumption ($nTCP$) being statistically significant at the 5% level and death rate (TT) being statistically significant at the 10% level. The R^2 for the fixed effects model is 84%, which explains that about 84% of variations in the CO_2 emissions is explained by the dependent variables, considered in the study. The intercept is –54.21, which indicates that when all variables are constant, ceteris paribus, the CO_2 emissions decrease by 54%. There is a positive relationship between death rate and CO_2 emissions, which indicates that a unit increase in death rate leads to a 15% increase in CO_2emissions. A unit increase in fertilizer consumption causes a 6.9% increase in CO_2 emissions. There is a positive relationship between agricultural land use and CO_2 emissions. Results show that a unit increase in agricultural land use leads to a 4.46% rise in CO_2emissions. The results indicate that a unit increase in fossil fuel consumption causes the CO_2 emissions to increase by 3.47%. The increase in both GDP per capita and total population are positive. Results show that a unit increase in each variable causes CO_2 emissions to increase by 3.70% and 0.906%, respectively.

Table 2. Panel regression results for six countries.

Variables	Fixed Effects (1) $lnECO2EPC_t$		Random Effects (2) $lnECO2EPC_t$	
	Coefficient	P-Value	Coefficient	P-Value
Constant	–54.214***	0.000	–7.258***	0.000
$lnDTRT_t$	0.147*	0.092	0.300**	0.021
$lnFRTCP_t$	0.069**	0.027	0.085**	0.021
$lnAGRL_t$	4.464***	0.000	–0.331***	0.000
$lnFFEC_t$	3.469***	0.000	3.188***	0.000
$lnGDPPC_t$	3.700***	0.000	–9.510***	0.000
$lnTPOP_t$	0.906***	0.000	–0.264***	0.000
R^2	84		62	
F-Stats	121.43			
Prob > F	0.000			
Hausman test	144.45 (0.000)			

Note: *** denotes statistical significance at the 1% level, ** at the 5% level and * at the 10% level.

From the results, **Table 3** highlights the diagnostic tests for all country-specific models. The conducted tests include Breusch-Pagan for heteroskedasticity, which indicates that all models for six countries do not suffer from heteroskedasticity as P-values are higher than 0.05. The second test was Breusch-Godfrey for autocorrelation which also indicates that all models are not suffering from autocorrelation as their P-values are higher than 0.05. Lastly, Durbin-Watson carries a value of 1.7 to 1.9 for the case of South Africa, USA, and Brazil, and this shows that the model does not suffer from autocorrelation. For India, Russia and China the values for Durbin-Watson are in the region of 2.3 to 2.4 which is not far from the threshold value of 2.4.

Table 4 shows the results for the panel data analyses for the combined six countries and individual countries. The variables are showing expected signs in different countries, which indicates that the CO_2 emissions have a positive relationship with selected variables irrespective of the country. The results show that the constant for combined countries is negative, which indicates that the CO_2 emissions decrease if other variables are constant, but the USA and China are opposite, which translates that keeping other variables constant, *ceteris paribus,* the CO_2 emissions increase by 3.7% and 14.74%, respectively. The fertiliser consumption is positive and statistically significant when estimating for combined six countries and the USA, but the rest of the other countries it is insignificant. The results impliy that a unit increase in fertiliser consumption globally and in the USA leads to at

Table 3. Diagnostic checks for all six countries.

	ZAF	USA	BRA	IND	RUS	CHN
Breusch-Pagan (Heteroskedasticity)	0.28 (0.594)	0.06 (0.806)	1.15 (0.283)	0.01 (0.926)	0.01 (0.926)	1.14
Breusch-Godfrey (Autocorrelation)	2.394 (0.122)	0.072 (0.788)	4.792 (0.07)	3.713 (0.06)	3.713 (0.06)	1.936 (0.164)
Durbin-Watson	1.9	1.7	1.9	2.4	2.4	2.3

Note: Values in parentheses represent the P-values.
Source: Computed from Field Survey Data, 2024.

least 6.9% and 13.1% CO_2 emissions, respectively.

The study revealed that fertilizer consumption significantly contributes to CO_2 emissions in the USA, where reliance on synthetic fertilizers is high. In comparison, Brazil, Russia, and India showed a negligible impact from fertilizer use on emissions, likely due to differing agricultural practices [21–38]. South Africa's emissions from fertilizer use were positive but less substantial, reflecting both a smaller agricultural sector and reliance on coal-based energy [39]. These findings suggest that countries with intensive fertilizer use, like the USA, could mitigate emissions by reducing synthetic fertilizer dependency.

All seven models have an R^2 of over 50%, which indicates that the variations of the dependent variable are explained by the selected independent variables. In the work of Dyuzheva and Tinkova [39], it stated that as of 2016, the USA accounted for 15% of the world's total fertilizer consumption. Fertilizer consumption is associated with capital intensification in the form of tractors and farm equipment and high consumption of energy in the form of diesel [40].

Looking at the effects of population size and GDP among developed countries such as China and the US, and comparing with that of South Africa, some important observations emerge. The coefficient of change for China's population size (β = 9.156, p < 0.01) is the highest among the six countries in the study sample. It is followed by the USA (β = 9.156, p < 0.05) and South Africa at (β = 1.474, p < 0.01). For every percentage change in population size, the rate of CO_2 emissions in China increases by more than 900%, whereas for the USA and South Africa, CO_2 emissions change by more than 100%.

This, when read together with the effects of GDP for the same countries, shows economic logic. The effects of GDP for China (β = 1.128, p < 0.01) towards CO_2 emissions are the largest followed by South Africa (β = 1.098, p < 0.01) and the USA in third place (β = 0.614, p < 0.05). The implications are that as the population of a country grows, there is high demand for food and high demand for energy resources. The activities related to food production and energy consumption increase CO_2 emissions. These results concur with the findings of Mrówczyńska-kamińska et al. [37], where for the study involving 14 countries, the researchers established that there was a cause-and-effect relationship between population density, energy use per capita, and CO_2 emissions. The impacts of other BRICS countries i.e. Brazil, Russia & India about population are small with a coefficient of less than zero and statistically not significant.

South Africa's reliance on coal-based energy resources impacts its CO_2 emissions, making it the leading greenhouse emitter in Africa. According to USAID [20] and Mirzania, Thompson and Muir [40], nearly 90% of the country's energy production is from coal, which contributes to high CO_2 emissions relative to countries with diversified energy mixes. This reliance, therefore, explains why, despite having a relatively smaller economy and population, South Africa's emissions levels are comparable to those of much larger economies, such as the USA and China [40]. In contrast, other BRICS countries like Brazil and Russia show lower dependency on coal, which contributes to their comparatively reduced CO_2 emissions [21].

Nations such as the US and China have made steps in diversifying their energy sources, while South Africa has maintained a coal-centric approach, with coal accounting for nearly 90% of its electricity production [41]. This reliance means that despite having a smaller population and economy, South Africa's emissions per unit of GDP remain high, indicating less efficient energy use and limited adoption of cleaner alternatives. Comparatively, countries with a more balanced energy mix benefit from a lower carbon footprint due to cleaner sources such as natural gas, nuclear, and renewables, which reduce their reliance on coal [42]. In order to reduce emissions and improve energy sustainability, South Africa would need to shift toward renewables and cleaner technologies, which could help bring its emission levels closer to those of its peers with diversified energy sources.

With regards to the GDP, the impact of Brazil is small and statistically non-significant, whereas those of Russia and India, although statistically significant, are small and with a coefficient of below zero.

Results from the hypothesis below have been empirically proven:

Hypothesis 1 (H_0). *Economic growth, fertilizer, and population growth in South Africa have significant negative impacts on CO_2 emissions comparable to those of the US and China.*

Drawing from these results, an important question to be asked relates to the impact of South Africa's population size and GDP considering that they are relatively small compared to those of China and the USA. This outcome can be attributed to South Africa's energy structure and efficiency, whereby coal serves as the biggest feedstock to the country's energy system and in relative terms, there exists limited clean energy supply. According to Mirzania, Thompson and Muir [40], as of 2020, in South Africa, coal-related energy accounted for 72.9% and renewable energy contributed 1.1% to total primary energy consumption. For the US, this figure for coal energy mix is 19.3%, for Brazil, 5.1%, China 56.8%, India 52.9% and Russia 12.3%. The world's coal share in the energy mix is projected to fall from 27% to 25% by 2023 [43]. China and the USA have over the years been diversifying the energy mix and through advancements in technology have achieved some level of efficiency when it comes to the consumption of fossil fuel energy [7, 44].

For a study that looked at the coupling or decoupling of economic growth energy demand during the period from 1990 to 2015, Wang and Jiang [32] found that the decoupling efforts in China and India delivered positive results. Improving energy efficiency in China shows signs of decreasing CO_2 emissions, while advancing technology is the major contributor to India's decoupling effort [32]. When it comes to fertilizer consumption, the impact is significant only for the US ($\beta = 0.131, p < 0.05$) and for all countries combined ($\beta = 0.069, p < 0.05$). This could be attributed to the high level of capital investments (e.g., farm equipment and implements and diesel) in that country.

The empirical results of this study reveal that economic growth and population size have a significant impact on CO_2 emissions in South Africa, a finding that concurs with the Environmental Kuznets Curve (EKC) theory [45]. According to the EKC, economic growth initially leads to increased environmental degradation [24], which in this case is reflected in higher CO_2 emissions due to factors such as reliance on coal-based energy and intensive agricultural practices. However, as economic development progresses, the theory suggests that countries can shift towards cleaner energy sources and sustainable agricultural practices, potentially reducing emissions [31]. This hypothesis may be supported by the observed patterns in South Africa's economic trajectory, where further development could see a shift towards more renewable energy adoption, aligning with the downward-sloping portion of the EKC.

Table 5 highlights the diagnostic tests for all country specific models. The conducted tests include Breusch-Pagan for heteroskedasticity, which indicates that all models for six countries do not suffer from heteroskedasticity as P-values are higher than 0.05. The second test was Breusch-Godfrey for autocorrelation which also indicates that all models are not suffering from autocorrelation as their P-values are higher than 0.05. Lastly, Durbin-Watson for validating the model with regards to autocorrelation, with an assumption that the value must be close to 2, and indeed all values of Durbin-Watson are close to 2.

5. Conclusions and Recommendations

The study objective was to compare the impact of South Africa's population growth, economic growth, and fertilizer consumption on CO_2 emissions, with those of the US and China and other BRICS countries. The hypothesis set out in the paper has been proven empirically. The results show that South Africa is comparable to the US and China when it comes to the effects of two variables, namely the effects of GDP growth and population size. This goes against the backdrop of South Africa having a relatively small size of economy and population. This outcome can be attributed to South Africa's high reliance on coal-based energy resources. The results also show that the impact of BRICS countries,

Table 4. The combined results of six countries and individual analysis per country.

Variables	All Countries *lnECO2EPC*		ZAF *lnECO2EPC*		USA *lnECO2EPC*		BRA *lnECO2EPC*		IND *lnECO2EPC*		RUS *lnECO2EPC*		CHN *lnECO2EPC*	
	Coef.	P-Value	Coef.	P-Value	Coef.	P-Value	Coef.	P-Value	Coef.	P-Value	Coef.	P-Value	Coef.	P-Value
Constant	–54.214***	0.000	–29.487***	0.000	3.735	0.799	–30.273***	0.000	–13.411	0.725	–13.411	0.725	14.734***	0.000
$lnDTRT_t$	0.147*	0.092												
$lnFRTCP_t$	0.069**	0.027	0.026	0.000	0.131**	0.024	0.017	0.705	0.058	0.172	0.058	0.172	0.212	0.280
$lnAGRL_t$	4.464***	0.000	4.910***	0.707	2.034**	0.045	1.526**	0.023	5.062*	0.067	5.062*	0.067	0.104	0.939
$lnFFEC_t$	3.469***	0.000	3.952***	0.000	5.167***	0.000	1.322***	0.000	0.930	0.590	0.930	0.590	3.283***	0.000
$lnGPDC_t$	3.700***	0.000	1.098***	0.000	0.614**	0.020	0.497	0.000	0.217**	0.020	0.217**	0.020	1.128***	0.000
$lnTPOP_t$	0.906***	0.000	1.474***	0.015	1.746**	0.047	0.344	0.299	0.404	0.854	0.404	0.854	9.156***	0.000
R^2	91		87		96		99		74		74		99	
F-Stats	255.52		33.93		100.46		509.74		9.83		9.83		1058.33	
F-stats (P-value)	0.000		0.000		0.000		0.000		0.000		0.000		0.000	

Note: *** denotes for statistical significance at the 1% level, ** at the 5% level and * at the 10% level.
Source: Computed from Field Survey Data, 2024.

Table 5. Diagnostic checks for all six countries.

	ZAF	USA	BRA	IND	RUS	CHN
Breusch-Pagan (Heteroskedasticity)	0.28 (0.594)	0.06 (0.806)	1.15 (0.283)	0.01 (0.926)	0.01 (0.926)	1.14 (0.081)
Breusch-Godfrey (Autocorrelation)	2.394 (0.122)	0.072 (0.788)	4.792 (0.07)	3.713 (0.06)	3.713 (0.06)	1.936 (0.164)
Durbin-Watson	1.9	1.7	1.9	2.4	2.4	2.3

Note: Values in parentheses represent the P-values.

such as Brazil, Russia, and India, in terms of population size, exhibits no impact on CO_2 emissions.

As a policy recommendation, South Africa needs to accelerate the diversification by investing significantly in renewable energy resources, such as solar, wind, and hydropower, as emphasized in the South Africa State of Renewable Energy report. The adoption of a comprehensive energy policy that integrates these renewable resources may assist South Africa in aligning itself with global efforts to mitigate climate change. This strategic shift would not only reduce greenhouse gas emissions but also create jobs and drive technological innovation.

Author Contributions

J.S.K. was responsible for conceptualization of the manuscript, literature review, the writing, investigations, organizing resources, data curation, preparation of the draft, reviewing and project administration. S.M. was responsible for organizing the software, doing data analysis, writing the methodology, visualization and project administration. I.A. provided supervision, reviewed the manuscript, provided validation and visualization. M.L., W.M. and L.P.M. assisted with literature review, project administration, formatting of the manuscript, validation of results and editing. M.L. was also responsible for streamlining the references and citations. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The study used panel data sourced from the World Bank's World Development Indicators ranging from 1960 to 2023.

Acknowledgments

The Agricultural Research Council (ARC) and National Agricultural Council (NAMC) are acknowledged for admin-

istrative and logistical support.

Conflicts of Interest

As authors and co-authors, we hereby declare that there is no conflict of interest and that the research study is meant to create awareness relating to status of CO_2 emissions for speciand the aim is to contribute to the body of knowledge. The funders had no role in the design of the study, in the collection, analysis or interpretation of data, in the writing of the manuscript or in the decision to publish the results.

References

[1] Trauernicht, C., 2019. Vegetation-rainfall interactions reveal how climate variability and climate change alter spatial patterns of wildland fire probability on big Islands, Hawai. Science of the Total Environment. 650, 459–469. DOI: https://doi.org/10.1016/j.scitotenv.2018.08.347

[2] Pontzer, H., 2021. Hotter and sicker: External energy expenditure and the tangled evolutionary roots of anthropogenic climate change and chronic disease. American Journal of Human Biology. 33(4), e23579. DOI: https://doi.org/10.1002/ajhb.23579

[3] Edeme, R.K., Emeka, E.T., Ogbuabor, J.E., 2024. Global uncertainty, climate change and the unemployment-economic growth relationship in Nigeria. Journal of Development Policy and Practice. 9(2), 238–256. DOI: https://doi.org/10.1177/24551333231208296

[4] Kang, M., Zhao, W., Jia, L., et al., 2020. Balancing carbon emission reductions and social economic development for sustainable development: Experience from 24 countries. Chinese Geographical Science. 30, 379–396. DOI: https://doi.org/10.1007/s11769-020-1117-0

[5] United Nations Framework Convention on Climate Change (UNFCCC), 1997. Kyoto Protocol to the United Nations Framework Convention on Climate Change. Kyoto Protocol, Kyoto. Kyoto Climate Change Conference; December 1–10, 1997; Kyoto, Japan. pp. 1–32.

[6] Chen, P., Nirula, A., Heller, B., et al., 2021. SARS-CoV-2 neutralizing antibody LY-CoV555 in outpatients with Covid-19. New England Journal of Medicine. 384(3), 229–237. DOI: https://doi.org/10.1056/NEJMoa2029849

[7] Yang, Y., Zhang, H. and Chen, X., 2020. Coronavirus pandemic and tourism: Dynamic stochastic general equilibrium modeling of infectious disease outbreak. Annals of Tourism Research. 83, 102913. DOI: https://doi.org/10.1016/j.annals.2020.102913

[8] Huang, C., Wang, Y., Li, X., et al., 2020. Clinical features of patients infected with 2019 novel coronavirus in Wuhan, China. The Lancet. 395(10223), 497–506.

[9] Ebi, K.L., Vanos, J., Baldwin, J.W., et al., 2021. Extreme weather and climate change: Population health and health system implications. Annual Review of Public Health. 42(1), 293–315. DOI: https://doi.org/10.1146/annurev-publhealth-012420-105026

[10] Zhang, M., Chen, E., Zhang, C., et al., 2024. Impact of seasonal global land surface temperature (LST) change on gross primary production (GPP) in the early 21st century. Sustainable Cities and Society. 110, 105572. DOI: https://doi.org/10.1016/j.scs.2024.105572

[11] Ortiz D.I., Piche-Ovares, M., Romero-Vega, L.M., et al., 2021. The impact of deforestation, urbanization, and changing land use patterns on the ecology of mosquito and tick-borne diseases in Central America. Insects. 13(1), 20. DOI: https://doi.org/10.3390/insects13010020

[12] Zhang, M., Tan, S., Liang, J., et al., 2024. Predicting the impacts of urban development on urban thermal environment using machine learning algorithms in anjing, China. Journal of Environmental Management. 356, 120560. DOI: https://doi.org/10.1016/j.jenvman.2024.120560

[13] Zhang, M., Zhang, Z., Tong, B., et al., 2023. Analysis of the coupling characteristics of land transfer and carbon emissions and its influencing factors: A case study of China. Frontiers in Environmental Science. 10, 1105552. DOI: https://doi.org/10.3389/fenvs.2022.1105552

[14] Li, A., Zhang, Z., Zhang, A., 2015. Why are there large differences in performances when the same carbon emission reductions are achieved in different countries?. Journal of Cleaner Production. 103, 309–318. DOI: https://doi.org/10.1016/j.jclepro.2014.08.022

[15] Dong, F., Zhu, J., Li, Y., Chen, Y., et al., 2022. How green technology innovation affects carbon emission efficiency: evidence from developed countries proposing carbon neutrality targets. Environmental Science Pollution Research. 29(24), 35780–35799. DOI: https://doi.org/10.1007/s11356-022-18581-9

[16] Chen, H., Lu J., Obobisa, E.S., 2023. Striving towards 2050 net zero CO_2 emissions: How critical are clean energy and financial sectors? Heliyon. 9(12), E22705. DOI: https://doi.org/10.1016/j.heliyon.2023.e22705

[17] Apeh, C.C., Agbugba, I.K., Mdoda, L., 2023. Assessing the determinants of adopting urban tree planting as climate change mitigation strategy in Enugu metropolis, Nigeria. Sustainability. 15(16), 12224. DOI: https://doi.org/10.3390/su151612224

[18] United Nations, 2016. Paris Climate Agreement, Signing Ceremony. List of Parties that signed the Paris Agreement on 22 April. Available from: https://ww.un.org (cited 25 September 2024).

[19] United Nations, 2023. Action on Climate and SDGs. Available from: https://unfccc.int/topics/cooperative-activities-and-sdgs/action-on-climate-and-sdgs (cited 13 September 2024).

[20] United States Agency International Development (USAID), 2023. Climate Change Country Profile Fact Sheet. Available from: https://www.usaid.gov/climate/country-profiles/south-africa (cited 29 August 2024).

[21] Rauf, A., Ali, N., Sadia, M.H., et al., 2023. Foreign direct investment, technological innovations, energy use, economic growth and environmental sustainability nexus: New perspectives in BRICS economies. Sustainability. 15(18), 14013. DOI: https://doi.org/10.3390/su151814013

[22] Sarkodie, S.A., Strazov, V., 2019. Effect of foreign direct investments, economic development and energy consumption on greenhouse gas emissions in developing countries. Science of the Total Environment. 646, 862–871. DOI: https://doi.org/10.1016/j.scitotenv.2018.07.365

[23] Kuznets, S., 1955. International differences in capital formation and financing. In: Abramovitz, M., Kuznets, S. (eds.). Capital Formation and Economic Growth. Princeton University Press: Princeton, NJ, USA. pp. 19–111.

[24] Cai, Y., Sam C.Y., Chang, T., 2018. Nexus between clean energy consumption, economic growth and CO_2 emissions. Journal of Cleaner Production. 182, 1001–1011. DOI: https://doi.org/10.1016/j.jclepro.2018.02.035

[25] Waheed, R., Chang, D., Sarwar, S., et al., 2017. Forest, agriculture, renewable energy and CO_2 emission. Journal of Cleaner Production. 172, 4231–4238. DOI: https://doi.org/10.1016/j.jclepro.2017.10.287

[26] Beckerman, W., 1992. Economic development and the environment: Conflict of complementarity? World Bank. Report No. 9667, Washington, DC, USA, March 1992.

[27] Acaroğlu, H., Kartal, H.M., García Márquez, F.P., 2023. Testing the environmental Kuznets curve hypothesis in terms of ecological footprint and CO_2 emissions through energy diversification for Turkey. Environmental Science and Pollution Research. 30(22), 63289–63304.

[28] Jan, H., Rizwan, M., 2023. An unexplored nexus of political freedom, economic growth, economic conditions and CO_2 emission in Asian country. Asian Bulletin of Contemporary Issues in Economics and Finance. 3(1), 45–62. DOI: http://dx.doi.org/10.62019/abcief.v3i1.33

[29] Akhbari, R., Nejati, M., 2019. The effect of corruption on carbon emissions in developed and developing countries: Empirical investigations of a claim. Heliyon. 5(9), e02516. Available from: https://www.cell.com/heliyon/fulltext/S2405-8440(19)36176-6

[30] Döring, T., Aigner-Walder, B., 2022. The limits to growth—50 years ago and today. Intereconomics. 57(3), 187–191.

[31] Nogueira, C., 2019. Contradictions in the concept of sustainable development: An analysis in social, economic and political contexts. Environmental Development. 30, 129–135. DOI: https://doi.org/10.1016/j.envdev.2019.04.004

[32] Wang, Q., Jiang, R., Zhang, L., 2019. Is decoupling economic growth from fuel consumption possible in developing countries? A comparison of China and India. Journal of Cleaner Production. 229, 806–817. DOI: https://doi.org/10.1016/j.jclepro.2019.04.403

[33] Zarco-Soto, I.M., Zarco-Periñán, P.J., Sánchez-Durán, R., 2021. Influence of cities population size on their energy consumption and CO_2 emissions: The case of Spain. Environmental Science and Pollution Research. 28, 28146–28167. DOI: https://doi.org/10.1016/j.jclepro.2019.04.403

[34] Ameyaw, B., Yao, L., 2018. Analyzing the impact of GDP on CO2 emissions and forecasting Africa's total CO2 emissions with non-assumption driven bidirectional long short-term memory. Sustainability. 10(9), 3110. Available from: https://www.mdpi.com/2071-1050/10/9/3110

[35] Doğan, N., 2019. The impact of agriculture on CO2 emissions in China. Panoeconomicus. 66(2), 257–271. DOI: https://doi.org/10.1155/2019/3415630

[36] Jebli, M.B., Youssef, S.B., 2017. The role of renewable energy and agriculture in reducing CO_2 emissions: Evidence for North Africa countries. Ecological Indicators. 74, 295–301. DOI: https://doi.org/10.1016/j.ecolind.2016.11.032

[37] Mrówczyńska-Kamińska, A., Bajan, B., Pawlowski, K.P., et al., 2021. Greenhouse gas emissions intensity of food production systems and its determinants. PLoS One. 16(40), e0250995. DOI: https://doi.org/10.1371/journal.pone.0250995

[38] Vijayakumar, S., Chatterjee, D., Subramanian, E., et al., 2023. Efficient management of energy in agriculture. In: Rakshit, A., Biswas, A., Sarkar, D., et al. (eds.). Handbook of Energy Management in Agriculture. Springer Nature: Singapore. 355–385. DOI: https://doi.org/10.1007/978-981-19-7736-7_18-2

[39] Dyuzheva, N.V. and Tinkova, A.A., 2019. Mineral fertilizer market consumption trends. RUDN Journal of Economics, 27(4), 722–731.

[40] Mirzania, D., Thompson, A.C., Muir, K.W., 2021. Applications of deep learning in detection of glaucoma: A systematic review. European Journal of Ophthalmology. 31(4), 1618–1642.

[41] Akinbami, O.M., Oke, S.R., Bodunrin, M.O., 2021. The state of renewable energy development in South Africa: an overview. Alexandria Engineering Journal. 60(6), 5077–5093. DOI: https://doi.org/10.1016/j.aej.2021.03.065

[42] IEA (International Energy Agency), 2021. World Energy Outlook 2021. Report No. WEO-2021, October 2021. Available from: https://www.iea.org/reports/world-energy-outlook-2021

[43] Barrera, M.A., Sabatella, I., Serrani, E., 2022. Macroeconomic barriers to energy transition in peripheral countries: The case of Argentina. Energy Policy. 168, 113117.

[44] Kaika, D., Zervas, E., 2013. The Environmental Kuznets Curve (EKC) theory-Part A: Concept, causes and the CO_2 emissions case. Energy Policy. 62, 1392–1402. DOI: https://doi.org/10.1016/j.enpol.2013.07.131

[45] Kuznets, S., 2019. Economic growth and income inequality. In: Seligson, M.A. (ed.). The Gap between Rich and Poor. Routledge: London, UK. pp. 25–37.